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The value of module efficiency in lowering the levelized cost of energy of photovoltaic systems

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ABSTRACT

One standard that is used to compare different energy generation technologies or systems is the levelized cost of energy (LCOE). The relatively high LCOE of photovoltaics (PV) is an obstacle to adopting it as a major electricity source for terrestrial applications. In a conventional PV system, the cost of the module contributes approximately half of the expense and the other costs are together summarized as balance of system (BOS). A large portion of the BOS is not related to the peak power of the system, but can be either proportional to or independent of the total installation area. Across different PV systems with the same installation area, this part of BOS ($/W) is directly dependent on the module efficiency. Therefore, the LCOE is affected by the module efficiency even if the module price ($/W) remains the same. In this paper, we compare the LCOE across PV systems with equal installation areas but with modules of different efficiencies installed with fixed tilt, 1-axis tracking or 2-axis tracking. We conclude that: (1) at a given module price in $/W, more efficient PV modules lead to lower LCOE systems; (2) when meeting an LCOE goal, the PV module efficiency has a lower limit that cannot be offset by module price; and (3) both 1-axis and 2-axis tracking installations provide lower LCOEs than fixed tilt installations.

Contents

1. Introduction

The photovoltaic (PV) industry is the fastest growing power industry in the world. In the last decade PV production grew by more than 35% per year [1,2]. Technological improvements, increased economies of scale, and strong policy support have contributed to this experience. Nevertheless, compared with traditional energy sources used to generate electricity, like fossil fuels, without policy support PV energy production is limited in its wider application because of its relative high cost. Cost reduction for PV can be achieved through combination of market, tax and regulatory incentives (e.g., tax credits, rebates, solar energy mandates) and research and development (R&D) support [2]. R&D funding is crucial for increasing energy efficiency of PV modules. As is shown in this paper, increased module efficiency can reduce levelized (i.e., lifetime) energy production costs of PV systems. This work compares the energy cost of PV systems that adopt different module efficiencies and different configurations. It also identifies approaches to achieve lower energy production costs for this technology.

One measure to compare different PV technologies is levelized cost of energy (LCOE), a concept that was introduced at the beginning. The LCOE is calculated using the solar advisor model (SAM) [3].

To compare the LCOE of systems with different module efficiencies and different configurations, we specify a reference system that

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allows the comparison to be implemented under the same baseline conditions. We choose a 1 MW commercial PV installation with fixed tilt angle at Phoenix, AZ and specify all the performance and financing parameters.

Starting from that reference system, we quantitatively analyze the influence of module efficiency on the LCOE of fixed tilt PV systems by evaluating the change in energy production and system expense as a function of module efficiency. The LCOE's dependence on module efficiency is displayed as a group of curves with each curve calculated for a particular module price. This group of curves shows that with PV modules of the same $/W value, those with higher module efficiencies lead to lower system LCOEs. The same information presented in another format demonstrates that there is a minimum required module efficiency below which the system LCOE cannot achieve a certain goal no matter how low the module cost.

Flat plate PV systems mounted on 1-axis and 2-axis trackers generate two additional sets of curves. These curves when compared with those for the fixed tilt system show that installations with trackers provide a lower LCOE.

Our comparisons across different PV technologies are based on a specific set of reference conditions. Varying these conditions can change the absolute values of the LCOEs, but the tendencies will be maintained: (1) Low LCOE requires high PV module efficiency and (2) tracking lowers the LCOE.

2. Levelized cost of energy (LCOE): a measure to characterize PV systems

The levelized cost of energy (LCOE) is "the cost that, if assigned to every unit of energy produced (or saved) by the system over the analysis period, will equal the total life-cycle cost (TLCC) when discounted back to the base year" [4]. The LCOE can be calculated using the following formula:

$$\mathrm{LCOE} = \frac{\mathrm{TLCC}}{\left(\sum_{n=1}^{N} Q_n/(1+d)^n\right)} = \frac{\left(\sum_{n=0}^{N} C_n/(1+d)^n\right)}{\left(\sum_{n=1}^{N} Q_n/(1+d)^n\right)} \quad (1)$$

where C_n is the cost for year n, Q_n is the energy output for the year n, d is the discount rate, N is the analysis period.

The discount rate appears in Eq. (1) to compensate for the time value in the currency. The LCOE in this work does not consider inflation and is called real LCOE; in contrast, LCOE that incorporates inflation is called nominal LCOE.

Eq. (1) requires two sets of information: (1) system cost items, payment method, financing and incentives; and (2) performance parameters and case study location. The first set determines the value of TLCC and the second set determines the actual energy output. In this work, we do not vary the payment method, financing and incentives, location, or performance parameters (other than module efficiency) so we can focus on the influence of PV module efficiency.

LCOE is calculated by running solar advisor model (SAM), a performance and economic model based on Eq. (1) that is designed to facilitate decision making for people involved in the renewable energy industry [3]. SAM was developed by the National Renewable Energy Laboratory (NREL) in collaboration with Sandia National Laboratories and in partnership with the U.S. Department of Energy (DOE) Solar Energy Technologies Program (SETP).

3. Reference system for LCOE analysis: 1 MW commercial system at Phoenix, AZ

The LCOE analysis is first performed on a commercial system that uses silicon flat plate modules with fixed tilt. The cost breakdown shown in Fig. 1 is cited from a technical report prepared by Rocky Mountain Institute in 2010 [5]. All the non-module cost items are summarized together as balance of system (BOS).

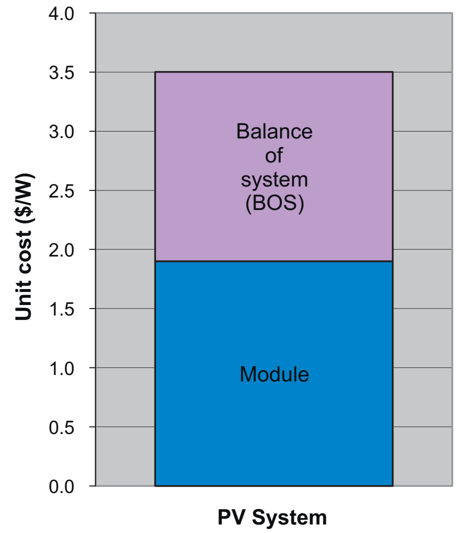


Fig. 1. Cost breakdown of the reference system, a representative of current best-practice conventional PV systems of ground-mounted (fixed tilt) type [5].

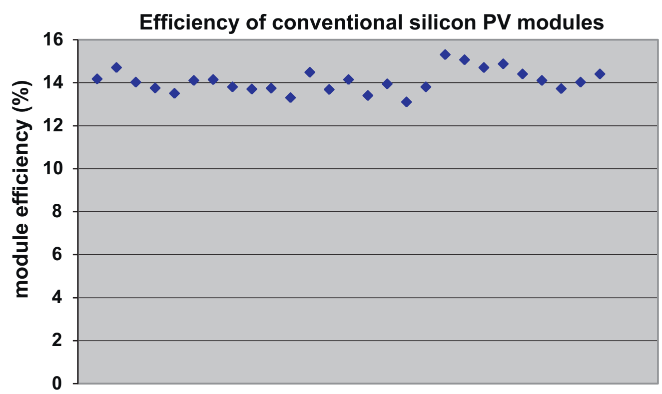


Fig. 2. Efficiency of silicon PV modules from 27 models across 11 brands, with module ratings over 200 W [6].

This reference system has a $3.5/W total installed cost and a $1.9/W module cost. The module efficiency is not specified but is described as "conventional PV". Currently, the efficiency of good conventional silicon modules lies in the range of 13–15% (see Fig. 2) so we choose 14% as the module efficiency for the reference system. The other system specifications are shown in Tables 1–3. Using these specifications, SAM calculates a LCOE of 10.71 ¢/kWh. Please note that 10.71 ¢/kWh is the energy cost to the manufacturer or the investor. Comparing with the electricity price on market requires that more tax considerations are incorporated and that the price for sale purpose is higher [4]. For instance, a good estimate of

Table 1
Reference commercial system: system location, scale and performance parameters.

Location	Phoenix, AZ
Capacity	1 MW
Total module area	7143 m^2
Module η	14%
Inverter η	96% [7]
System derate	88.5%
System degradation	0.5% [8]
Temperature sensitivity of the module performance	−0.5%/°C
Tilt angle	Fixed, latitude

Table 2
Reference commercial system: financing and incentives.

Payment method	Cash
Analysis period	30 years
Inflation rate	2.50%
Real discount rate	5.50%
State tax	8%
Federal tax	35%
Property tax	2%/year
Insurance	1%/year
ITC	Federal 30% [9]
State depreciation	MACRS half-year convention
Federal depreciation	MACRS half-year convention

the market price is 17.9 ¢/kWh, a value that results from dividing 10.71 ¢/kWh by 60%, while 40% is used as the marginal income tax rate of the investor. Given the same tax rate, 6 ¢/kWh LCOE to the manufacturer or the investor corresponds to approximately 10 ¢/kWh market electricity price.

4. The influence of module efficiency on LCOE for flat plate PV systems with fixed tilt

Starting from the reference system, we explore the LCOE's dependence on the module efficiency. We use Eq. (1) to derive the LCOE curve.

First, the value of the denominator is calculated. In our analysis, we adopt a simple efficiency model that assumes that the PV modules can work with a constant nominal efficiency. This is a simplified assumption since the real operation efficiency varies somewhat when the current–voltage (I–V) curve shifts as the irradiation changes. However, it is a reasonable model since we aim to explore the relationship between module efficiency and the cost of energy. Therefore, for constant module area, if the efficiency of the new module is η_{new}, then Q_n in Eq. (1) equals $\eta_{\text{new}}/\eta_{\text{ref}}$ times the Q_n of the reference system ($Q_{n(\text{ref})}$), and the denominator can be expressed as:

$$\left(\sum_{n=1}^{N}\frac{Q_n}{(1+d)^n}\right)_{\text{new}} = \sum_{n=1}^{N}\frac{Q_{n(\text{ref})}\cdot(\eta_{\text{new}}/\eta_{\text{ref}})}{(1+d)^n} = \frac{\eta_{\text{new}}}{\eta_{\text{ref}}}\cdot\left(\sum_{n=1}^{N}\frac{Q_n}{(1+d)^n}\right)_{\text{ref}} \quad (2)$$

Second, TLCC, the numerator of Eq. (1), is examined. There are two types of cost: installed cost and operating cost. For our analysis, cash is chosen as the payment method so the installed cost is paid at the beginning of the installation, or Year Zero. Other cash flow occurs in the following years throughout the whole analysis period and includes O&M cost, property tax, insurance, tax saving on these deductible expenses, and investment tax credit (ITC). Most of these cost and saving items since the first year are proportional to the installed cost that happens in Year Zero. Only a minor portion is related to O&M cost. For analysis transparency, we approximate linearity between TLCC and installed cost. Then the numerator of Eq. (1) can be expressed as:

Table 3
Reference commercial system: total installed cost, O&M and LCOE.

Module	$1.9/W
BOS	$1.6/W
Total installed cost	$3.5/W
O&M: inverter replacement	15th year: $0.2/W (2010 $) [5]
O&M: others	25 $/kW-year [5]
LCOE (real)	10.71 ¢/kWh

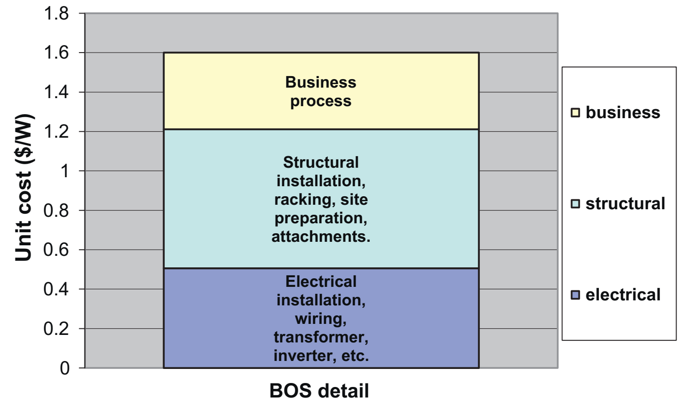


Fig. 3. BOS cost breakdown of the reference system, a representative of current best-practice conventional PV systems of ground-mounted (fixed tilt) type [5].

$$\text{TLCC}_{\text{new}} = \text{TLCC}_{\text{ref}}\cdot\frac{\text{TIC}_{\text{new}}}{\text{TIC}_{\text{ref}}} \quad (3)$$

where TIC denotes total installed cost spent at the beginning of the installation in units of US dollars. Combining Eqs. (2) and (3), the LCOE of a new system with a different module efficiency can be expressed by:

$$\begin{aligned}\text{LCOE}_{\text{new}} &= \frac{\text{TLCC}_{\text{new}}}{\left(\sum_{n=1}^{N}Q_n/(1+d)^n\right)_{\text{new}}}\\ &= \frac{\text{TLCC}_{\text{ref}}\cdot(\text{TIC}_{\text{new}}/\text{TIC}_{\text{ref}})}{\left(\sum_{n=1}^{N}Q_n/(1+d)^n\right)_{\text{ref}}\cdot(\eta_{\text{new}}/\eta_{\text{ref}})}\\ &= \text{LCOE}_{\text{ref}}\cdot\frac{\text{TIC}_{\text{new}}/\text{TIC}_{\text{ref}}}{\eta_{\text{new}}/\eta_{\text{ref}}} \quad (4)\end{aligned}$$

Rearranging Eq. (4) gives the ratio of the new LCOE to the LCOE of the reference system:

$$\begin{aligned}\frac{\text{LCOE}_{\text{new}}}{\text{LCOE}_{\text{ref}}} &= \frac{\text{TIC}_{\text{new}}/\text{TIC}_{\text{ref}}}{\eta_{\text{new}}/\eta_{\text{ref}}} = \frac{\text{TIC}_{\text{new}}/\eta_{\text{new}}}{\text{TIC}_{\text{ref}}/\eta_{\text{ref}}}\\ &= \frac{\text{TIC}_{\text{new}}/(\eta_{\text{new}}\cdot A_{\text{module}})}{\text{TIC}_{\text{ref}}/(\eta_{\text{ref}}\cdot A_{\text{module}})} = \frac{\text{TIC}_{\text{new}}/P_{\text{new}}}{\text{TIC}_{\text{ref}}/P_{\text{ref}}} = \frac{\text{UIC}_{\text{new}}}{\text{UIC}_{\text{ref}}} \quad (5)\end{aligned}$$

where A_{module} is the total area of the module, a constant parameter in our analysis; P is the peak power of the system; and UIC is the unit installed cost in units of $/W. The installed cost is composed of module cost and BOS cost. Since module cost varies with module efficiency, it will be set as a variable. Only BOS is analyzed below.

Fig. 3 shows that BOS is divided into three groups: electrical system, structural system, and business processes. The first part, the electrical system, includes inverter, wiring, transformer and relevant installations. Since electrical equipment usually has a power rating, the total required cost of these items is considered linearly proportional to the peak power of the specific PV system. Accordingly, the electrical installation cost is also considered linearly proportional to the system power capacity. Therefore, all of the electrical system cost is power-related cost, or PRC.

The second part of the BOS, the structural system, includes site preparation, racking and relevant installations. Since these costs are linearly proportional to the total area of the modules, the structural system cost is area-related cost, or ARC.

The third part of the BOS, the business processes, including financing and contractual costs, permitting, interconnection etc., is usually constant so this cost is fixed cost, or FC.

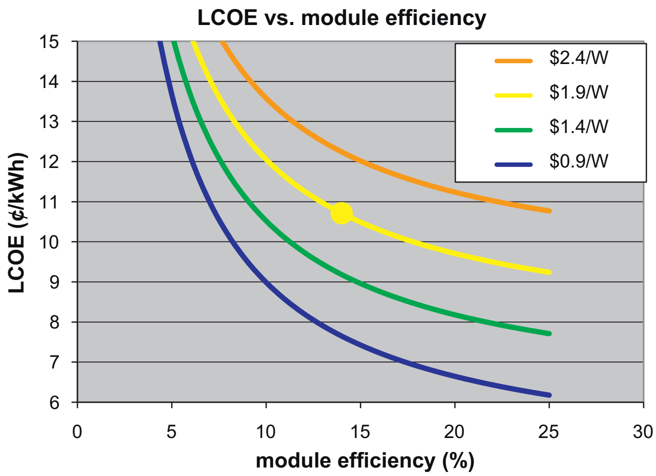


Fig. 4. LCOE as a function of module efficiency and module price. All systems are flat plate PV installations with fixed tilt at Phoenix, AZ.

Fig. 3 indicates that the ratio of the three components in the BOS is PRC:ARC:FC = 1:1.393:0.770. Since, in our analysis, the total module area is considered constant, the total ARC and total FC are not dependent on the power capacity of the system, nor on the module efficiency. Thus, as module efficiency changes, the total power (W) varies linearly, but the total ARC ($) and the total FC ($) remain constant. So ARC plus FC expressed in units of $/W is inversely proportional to the module efficiency. On the other hand, when module efficiency varies, the total PRC ($) changes linearly in proportion to the power capacity (W), so the PRC expressed in units of $/W remains constant. Therefore, Eq. (5) can be rewritten as:

$$\frac{\text{LCOE}_{\text{new}}}{\text{LCOE}_{\text{ref}}} = \frac{\text{UIC}_{\text{new}}}{\text{UIC}_{\text{ref}}} = \frac{\text{MUC}_{\text{new}}(\$/\text{W}) + (\text{FC}_{\text{ref}}(\$/\text{W}) + \text{ARC}_{\text{ref}}(\$/\text{W}))\cdot(\eta_{\text{ref}}/\eta_{\text{new}}) + \text{PRC}_{\text{ref}}(\$/\text{W})}{\text{UIC}_{\text{ref}}(\$/\text{W})} \tag{6}$$

where MUC denotes module unit cost in units of $/W. Our reference system has a BOS of $1.6/W, of which $1.094/W is the ARC plus FC and $0.506/W is the PRC (see Fig. 3). Substituting these values into Eq. (6) gives:

$$\frac{\text{LCOE}_{\text{new}}}{\text{LCOE}_{\text{ref}}} = \frac{\text{MUC}_{\text{new}}(\$/\text{W}) + \$1.094/\text{W}\cdot(14\%/\eta_{\text{new}}) + \$0.506/\text{W}}{\$3.5/\text{W}} \tag{7}$$

Eq. (7) predicts that for a given $/W module cost, higher efficiency leads to lower LCOE. This value of module efficiency resides in the ARC and FC term (shown as $1.094/W·(14%/$\eta_{\text{new}}$)) in Eq. (7). Fig. 4 shows the dependence of LCOE on module efficiency. The different curves correspond to different module prices. The yellow dot represents the reference system.

Fig. 4 illustrates the inverse proportionality between the LCOE and the module efficiency for a given module price in units of $/W. Comparing across curves for different module prices shows that, as module price decreases, LCOE's sensitivity to module efficiency increases.

Since the module price (in units of $/W) combines the pure module price metric (in units of $/m^2) with the module efficiency, we derive another group of LCOE curves that separates the pure

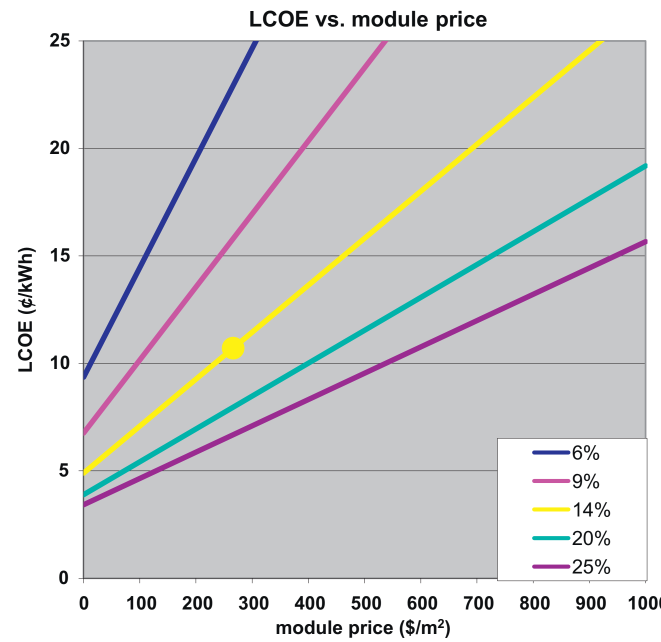


Fig. 5. LCOE as a function of module efficiency and module price. All systems are flat plate PV installations with fixed tilt angle at Phoenix, AZ.

module price metric from the module efficiency. The module price conversion is:

$$\text{MUC}(\$/\text{W}) = \frac{\text{MUC}(\$/\text{m}^2)}{1000\,\text{W}/\text{m}^2\cdot\eta} \tag{8}$$

Replacing MUC($/W) in Eq. (7) with Eq. (8) gives:

$$\frac{\text{LCOE}_{\text{new}}}{\text{LCOE}_{\text{ref}}} = \frac{(\text{MUC}_{\text{new}}(\$/\text{m}^2)/(1000\,\text{W}/\text{m}^2\cdot\eta_{\text{new}})) + \$1.094/\text{W}\cdot(14\%/\eta_{\text{new}}) + \$0.506/\text{W}}{\$3.5/\text{W}} \tag{9}$$

Thus for a given efficiency, the LCOE is linearly proportional to the module cost so the plots form straight lines (Fig. 5). As module efficiency varies, both the slope and the *y*-intercept of the line change. The slope reflects how the LCOE responds to a unit increment in module price. Systems with more efficient modules display milder slopes because a given increment in module price will be shared by more energy output (see Eq. (4)), so the increase in LCOE will be smaller. Therefore, the slope is inversely proportional to the module efficiency. On the other hand, the *y*-intercept of the curve denotes the LCOE value when the module is free, i.e., when the total installed cost is only composed of BOS cost. If BOS expenses had only PRC components, with module efficiency variation, both the total power (W) and the BOS cost ($) would change linearly, so the system's total installed cost ($/W) would remain constant and does not depend on module efficiency. This means that if BOS expenses are all PRC components, the intercept of the LCOE curve is not affected by module efficiency. However, this efficiency is important because ARC and FC are part of the BOS. As efficiency varies, the ARC and FC stay the same because the total module area does not change; this part of the cost is shared by more energy in systems with more efficient modules. So higher module efficiencies will lead to smaller values for the LCOE intercept. The relationship between the LCOE intercept and the module efficiency shows that keeping LCOE below some target value requires constraining the module efficiency; e.g.

Table 4
Module price necessary for different types of PV modules to achieve particular LCOE goals. The (percentages) in the 8 ¢/kWh and 6 ¢/kWh columns are relative module cost reductions compared with the values in the 10.7 ¢/kWh column.

Module type	Module efficiency	Module $/W for 10.7 ¢/kWh	Module $/W for 8 ¢/kWh	Module $/W for 6 ¢/kWh
High eff Si	19.5%	2.21	1.32 (−40%)	0.67 (−70%)
Conventional Si	14%	1.90	1.01 (−47%)	0.36 (−81%)
Thin film CdTe	11%	1.60	0.72 (−55%)	0.06 (−96%)
Others (low η)	6%	0.44	Never	Never

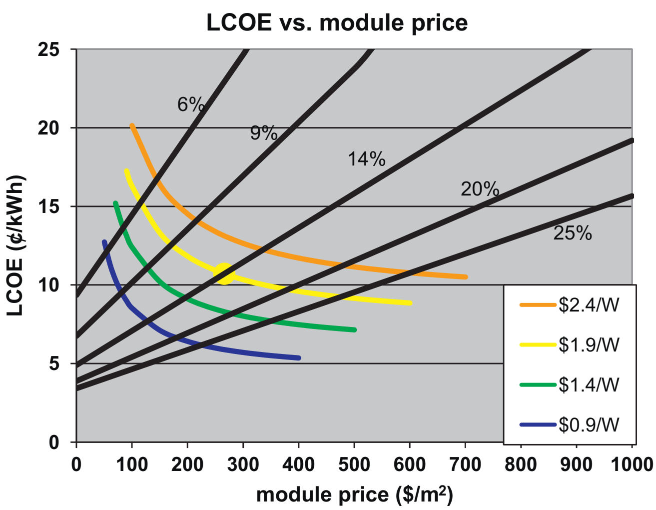


Fig. 6. LCOE as a function of module efficiency and module price. All systems are flat plate PV installations with fixed tilt angle at Phoenix, AZ.

if the target LCOE is 5 ¢/kWh, the module efficiency must be greater than 14% because efficiencies lower than this value will lead to a higher LCOE even when the modules are free.

In the same coordinate system as Fig. 5, we add plots of LCOE versus module price (in units of $/m^2) for several particular module prices (in units of $/W) (Fig. 6). For a given $/W module price, larger $/m^2 corresponds to higher module efficiency (see Eq. (8)), so the curved lines show that, LCOE decreases as module efficiency increases. This result agrees with the conclusion from Fig. 4.

We apply the preceding analyses to data from four types of commercial PV modules: high efficiency Si modules, conventional Si modules, thin film CdTe modules, and low efficiency modules. For these four types, we choose the module efficiencies given in Table 4. For high efficiency Si modules, we choose the module efficiency of SunPower E19/318 product [10]; for thin film CdTe modules, we choose the module efficiency of First Solar FS-380 product [11]. For the other types of modules of low efficiency, a 6% is chosen in the analysis. Using these module efficiencies, Eq. (7) can calculate the module price in units of $/W for a particular LCOE goal. Table 4 shows the module prices necessary for the different modules to achieve three LCOE goals.

Comparing the data in a given column shows that, to achieve the same LCOE goal, high module efficiency allows the module price in units of $/W to be high while low module efficiency requires a low module price. In fact, for certain LCOE goals, low efficiency modules require a negative module price (indicated as "never" in Table 4). Please note that our conclusions are valid when the BOS conditions are the same across modules. In specific cases, a change in BOS cost assumptions would affect the quantitative conclusions.

Looking across columns, we see that the required module price decreases as the LCOE value gets smaller. The relative module price reduction, marked as percentages in the 8 ¢/kWh and the 6 ¢/kWh columns (compared with the 10.7 ¢/kWh column) is more significant for low efficiency modules. Thus the sensitivity to module efficiency is more intense when the LCOE target is lower.

5. LCOE comparison between flat plate PV systems with fixed tilt and with tracking

The above analysis is for flat plate PV systems with fixed tilt but our qualitative conclusions also apply to flat plate PV systems with tracking. Thus higher module efficiency still corresponds to lower LCOE when the module price is maintained constant in units of $/W; and a minimum module efficiency is still required to achieve a LCOE goal no matter how low the module price. However, quantitatively the LCOE curves in Fig. 4 must change for tracking PV systems since there is an increase in both captured energy and installed cost of trackers. The captured energy can be calculated by SAM since the program provides different array tilt options, including fixed tilt, 1-axis and 2-axis. The cost of the tracker itself and its associated costs are all area-related. While this cost may vary from case to case, we use $74/m^2 and $94/m^2 for the extra cost in 1-axis and 2-axis tracking systems, respectively. Table 5 shows the derivation of these two numbers. The original data comes from a cost analysis by a German tracker system manufacturer, Deger Energie GmbH [12] that compares three configurations and finds the extra cost of 1-axis and 2-axis tracking systems to be €57/m^2 and €72/m^2, respectively. Using 1/1.3 as the exchange ratio of the Euro to the US dollar, the two numbers convert to $74/m^2 and $94/m^2. These translate to tracker price of $0.53/W and $0.67/W for systems using 14% efficient modules. Then SAM calculates LCOEs for 1-axis and 2-axis tracking systems of 9.28 ¢/kWh and 9.29 ¢/kWh, respectively. The decrease of the LCOE by utilizing tracking comes from the fact that, the increase of energy production caused by more captured irradiation is greater than the increase of cost introduced by the trackers expenses. For instance, the energy production gain is 30% by applying 1-axis tracking while the increase of the installed system cost is 15%, leading to a net decrease of the unit installed cost ($/W) (see Eq. (5)) by 12%. Please note this is slightly different from the decrease of LCOE, which is 13%. This is because Eq. (5) is proposed to better understand the value of module efficiency, and it is

Table 5
Information to derive the extra cost of tracking systems compared to fixed installation systems, from an article published in Photon International, November 2009 [12].

	Dual-axis tracking (DEGERtraker 7000NT)	Single-axis tracking (TOPtracker 40NT)	Fixed installation
Solar module area (m^2)	4884	5373	6716
Cost of tracker or mounting system and foundations (€)	602,658	579,835	343,750
Unit cost (€/m^2)	123	108	51
Extra cost compared with fixed (€/m^2)	72	57	–

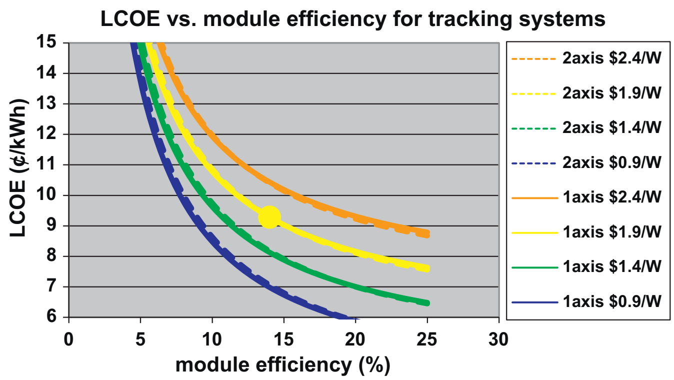


Fig. 7. LCOE as a function of module efficiency and module price. The systems are flat plate PV installations with 1-axis or 2-axis tracking at Phoenix, AZ.

based on the assumption that all the cash flow during the total life cycle is proportional to the installed system cost. In real cases, there is a small group of cash flow related to O&M (see the derivation of Eq. (3)).

With the modified system cost, Eq. (7) can be updated for 1-axis as Eq. (10) and for 2-axis as Eq. (11):

$$\frac{\mathrm{LCOE_{new}}}{\mathrm{LCOE_{ref}}} = \frac{\mathrm{UIC_{new}}}{\mathrm{UIC_{ref}}} = \frac{\mathrm{MUC_{new}}(\$/\mathrm{W}) + \$1.624/\mathrm{W}\cdot(14\%/\eta_{new}) + \$0.506/\mathrm{W}}{\$3.5/\mathrm{W} + \$0.53/\mathrm{W}} \quad (10)$$

$$\frac{\mathrm{LCOE_{new}}}{\mathrm{LCOE_{ref}}} = \frac{\mathrm{UIC_{new}}}{\mathrm{UIC_{ref}}} = \frac{\mathrm{MUC_{new}}(\$/\mathrm{W}) + \$1.764/\mathrm{W}\cdot(14\%/\eta_{new}) + \$0.506/\mathrm{W}}{\$3.5/\mathrm{W} + \$0.67/\mathrm{W}} \quad (11)$$

The LCOE curves based on Eqs. (10) and (11) are plotted in Fig. 7 and show that the LCOE of 1-axis and 2-axis tracking systems are quite close. Fig. 8 compares the LCOE of the 1-axis tracking system with that of the fixed tilt system. It shows that the LCOE of tracking systems is lower. Also, for a particular module price, the LCOE curves of the two configurations are not parallel. The decrease in LCOE with increasing module efficiency is faster for the tracking system than for the fixed tilt system, i.e., the LCOE in tracking systems is more sensitive to module efficiency. Eq. (6) explains this sensitivity. The module efficiency lies in the term with the ARC and FC so increasing ARC (by adding tracking into the system) increases the effect of this term on LCOE.

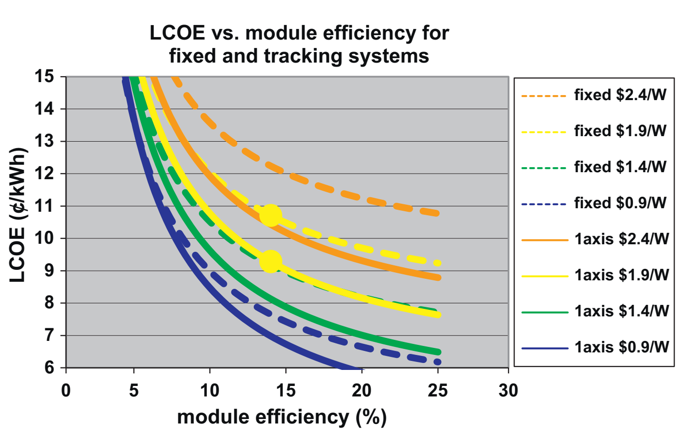


Fig. 8. LCOE as a function of module efficiency and module price. The systems are flat plate PV installations with fixed tilt and with 1-axis tracking at Phoenix, AZ.

6. Conclusions and future work

We use LCOE as a measure to compare PV systems across different module efficiencies that are installed with fixed tilt, 1-axis tracking and 2-axis tracking configurations. Since the BOS expense contains an area-related component and a fixed component, the LCOE is dependent on module efficiency. We find that (1) at a given module price (in units of $/W), PV modules with higher efficiency lead to systems with lower LCOEs; and (2) in order to achieve a LCOE goal, PV module efficiency must be constrained even if the module price is low. By comparing the LCOE of fixed tilt installations with those of 1-axis and 2-axis tracking installations, we conclude that: (1) both 1-axis and 2-axis tracking lead to lower LCOE than fixed tilt installations; and (2) LCOE is more sensitive to module efficiency in tracking systems than in fixed tilt systems. Therefore, high module efficiency and tracking configuration are two significant approaches to lowering the LCOE of PV systems, making them competitive with traditional energy sources in the future.

As described in this paper, module efficiency lowers the LCOE through the area-related and fixed components in the BOS. All our quantitative analyses are established on a set of BOS baseline conditions. However, the non-module cost in a PV system can vary significantly and depends strongly on the size of installation and the installers [13]. While the BOS breakdown shown in Fig. 1 cites that it is for "current best-practice conventional PV systems of ground-mounted type", the BOS cost in specific cases can be much higher [14]. In these cases, the business process usually occupies a much larger portion of the total BOS than that shown in Fig. 1, and thus leads to even more intense sensitivity of the LCOE to module efficiency.

Currently, the highest demonstrated efficiency of PV module adopting single junction as the receiver is 22.9% [15]. For higher module efficiency, multi-junction solar cells are designed in the same system to optimally absorb different spectrum sub-bands [16]. Prototype sub-modules containing multiple junctions have been reported to have efficiency close to 40% [15,17–20]. Since these multi-junction solar cells are of higher cost, they are usually designed in concentrating photovoltaic (CPV) modules. The LCOE analysis for flat plate PV system deployed in this work can be extended to CPV systems, and the basic concept about the value of module efficiency in reducing the system LCOE still applies. In CPV systems, the cost of the solar cell is to be close to that in flat plate PV system by reducing the required solar cell area with a factor equal to the concentration ratio; on the other hand, the non-module cost is increased by the trackers of high pointing accuracy. Since these trackers are area-related, the fraction of the ARC and FC in CPV system is even higher and the LCOE is more sensitive to the module efficiency. More detailed analysis about the value of module efficiency in reducing the CPV system LCOE is to be deployed in future work.

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